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Implementation of the Johnson-Holmquist II (JH-2) Constitutive Model Into DYNA3D

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Implementation of the Johnson-Holmquist II (JH-2) Constitutive Model Into DYNA3D

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Abstract

This report describes the implementation of a fully three-dimensional rate, pressure, and damage-dependent constitutive model for brittle materials such as ceramics into the explicit, Lagrangian finite element code DYNA3D. The model, otherwise known as the Johnson-Holmquist II (JH-2) ceramic model, has also been implemented into CTH, EPIC, and LS-DYNA, and is used extensively in modelling the brittle response of ceramics in armor applications. The DYNA3D material driver was used to verify the model implementation for constant strain-rate input histories (Johnson, G. R., and T. J. Holmquist. "An Improved Computational Constitutive Model for Brittle Materials." *High Pressure Science and Technology,* New York: AIP Press, 1993). Also described is the implementation of the JH-3 ceramic model and capabilities for modelling projectile dwell phenomena. The Johnson-Holmquist series of ceramic models (JH-1, JH-2, and JH-3) is currently being used in a broader program aimed at computational optimization of composite lightweight armor for Future Combat System vehicles.

Acknowledgments

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1. Introduction

This report describes the implementation of a fully three-dimensional (3-D) rate, pressure and damage-dependent constitutive model for brittle materials such as ceramics into the explicit, Lagrangian finite element code DYNA3D. The DYNA3D source code was obtained from Lawrence Livermore National Laboratories (LLNL) under the auspices of the U.S. Army Research Laboratory (ARL)-LLNL collaborator's agreement. The model, otherwise known as the Johnson-Holmquist II (JH-2) ceramic model, has also been implemented into CTH, EPIC, and LS-DYNA (model 110 in version 960 of the commercial code developed by Livermore Software Technology Corporation [LSTC]), and is used extensively in modelling the brittle response of ceramics in armor applications. This report outlines the important features of the JH-2 material model, the numerical implementation, and validation of the model implementation using the DYNA3D material model driver for constant strain-rate input histories. Despite the fact that the DYNA3D finite element code possesses over 40 constitutive models, few models (e.g., Fahrentold Brittle Damage [model 40]; Defense Threat Reduction Agency [DTRA] Concrete/Geological material [model 45]) are capable of simulating the rate- and pressure-dependent behavior observed in brittle ceramic materials. Hence, the current JH-2 model implementation provides an important phenomenological tool for armor designers involved in simulation-based design of composite integral armors.

2. Constitutive Model

The original Johnson-Holmquist brittle ceramic model (JH-1) is described in Johnson and Holmquist (1992), and represents a phenomenological description of brittle material behavior that includes pressure-dependent strength, strain-rate effects, and damage induced dilatation or bulking effects. In the following year, the model was improved to account for, among other things, the gradual-softening behavior that is observed in ceramics subjected to flyer-plate impact (Johnson and Holmquist 1993). The improved JH-2 model was implemented in both Lagrangian (EPIC) and Eulerian (CTH) hydrocodes where it was used in a number of studies aimed at predicting the depth-of-penetration (DOP) of long rod penetrators. Interestingly, even though the "so-called" improved JH-2 model captures the post-failure behavior of ceramics, it tends to overpredict the DOP (e.g., on the order of 13% [Meyer 1995] in AD995), while the JH-1 model tends to underpredict the DOP by only a few percent. This behavior is attributed to the fact that the JH-2 ceramic model continually degrades the yield strength as damage accumulates $0 < D < 1$, whereas strength degrades instantaneously for the JH-1 model only after $D = 1$. The most recent JH-3 model incorporates most features of the JH-2 model, most notably the power-law relationship between effective stress and pressure, as well as ceramic dwell phenomenology. More recently, researchers using the JH-1 ceramic model in the EPIC code have demonstrated that ceramic dwell can only be simulated using hybrid algorithms that couple Lagrangian and particle methods (e.g., general particle algorithms [GPA]) (Beissel and Johnson 2001). Apparently, tensile waves are artificially introduced into the computations when Lagrangian elements are removed from the calculations during penetration, which can cause premature

material failure. However, the use of hybrid Lagrangian/meshless methods may not be the only means to computationally simulate ceramic dwell phenomena; the development of more robust microphysically based constitutive models for ceramics or novel element erosion algorithms (Simha et al. 2002) might also provide a means for accurately modelling projectile dwell without the need to resort to particle or other meshless methods.

A thorough description of the JH-2 model can be found in Johnson and Holmquist (1993), and only those equations needed for description of the algorithmic implementation are reproduced here. Generally speaking, the normalized equivalent stress can be written as a power-law function of hydrostatic pressure shown in Figure 1, which illustrates continuous curves for the intact strength, σ_i^*, where $D = 0$, damaged strength, σ^*, where $0 < D < 1$, and fully fractured strength, σ_f^*, where $D = 1$, for the ceramic material. The general expression governing these curves is given by

$$\sigma^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*) \quad , \tag{1}$$

where D is a scalar damage parameter defined over the range $0 \leq D \leq 1$, and the stresses in equation (1) are made dimensionless by normalizing them to the equivalent stress at the Hugoniot Elastic Limit (HEL) through

$$\sigma^* = \sigma/\sigma_{HEL} \quad . \tag{2}$$

The normalized intact strength σ_i^* is given by

$$\sigma_i^* = A(P^* + T^*)^N(1 + C\ln\dot{\varepsilon}^*) \quad , \tag{3}$$

and the normalized fracture strength σ_f^* is given by

$$\sigma_f^* = B(P^*)^M(1 + C\ln\dot{\varepsilon}^*) \quad , \tag{4}$$

are illustrated in Figure 1 for $C = 0$. Pressure in equations (3) and (4) are made dimensionless by normalizing to the pressure at the HEL through

$$P^* = P/P_{HEL} \quad , \tag{5}$$

and $T^* = T/P_{HEL}$ is the normalized maximum tensile fracture strength. Note that T^* approaches zero as D approaches 1. The additional material constants are A, B, C, M, and N. All damage is assumed to accumulate through incremental plastic $\Delta\varepsilon^p$ deformation of the ceramic using an expression similar to that in the Johnson-Cook fracture model (Johnson and Cook 1985)

$$D = \sum \Delta\varepsilon^p/\varepsilon_f^p \quad , \tag{6}$$

where the rate-independent plastic strain to fracture is given by the power-law expression

$$\varepsilon_f^p = D_1(P^* + T^*)^{D_2} \quad . \tag{7}$$

Under dynamic loading, the equation-of-state (EOS) for the brittle-material can be defined by a polynomial expression that is written in terms of the excess compression μ (see also Kohn [1969])

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \quad , \tag{8}$$

where $\mu = \rho/\rho_0 - 1$, and ρ_0, ρ are the initial and final densities, respectively. K_1, K_2, and K_3, are constants determined from plate impact or diamond anvil press experiments. A pressure increment ΔP is added when damage begins to accumulate, $D > 0$, and represents an increase in potential energy as the deviatoric stresses decrease due to material softening. The internal energy U is quadratically related to the equivalent plastic flow stress σ_y

$$U = \sigma_y^2 \big/ 6G \quad , \tag{9}$$

where G is the shear modulus. Hence, the incremental energy loss ΔU can be computed as the difference between successive damage states using

$$\Delta U = U_{D(t)} - U_{D(t+\Delta t)} \quad . \tag{10}$$

If the energy loss ΔU is converted to a potential hydrostatic pressure increase ΔP, an approximate energy conservation relation can be written as

$$(\Delta P_{t+\Delta t} - \Delta P_t)\mu_t + (\Delta P^2_{t+\Delta t} - \Delta P_t^2)\big/2K_1 = \beta\Delta U \quad , \tag{11}$$

where β governs the fraction of elastic energy converted to potential energy. The implementation utilizes the current excess compression μ_t in contrast to the updated value $\mu_{t+\Delta t}$ used by Johnson and Holmquist (1992). Solving for the updated $\Delta P_{t+\Delta t}$ yields the expression

$$\Delta P_{t+\Delta t} = -K_1\mu_t + \sqrt{(K_1\mu_t + \Delta P_t)^2 + 2\beta K_1 \Delta U} \quad . \tag{12}$$

3. Numerical Implementation

A flowchart depicting the numerical implementation algorithm for the equations described in the previous section is outlined in Table 1. Validation of the algorithm and numerical implementation is also demonstrated using the DYNA3D material driver which allows the user to specify an arbitrary strain input history for prediction of the stress state at a material point. The material driver capability present in DYNA3D permits investigation of fundamental material behavior in the absence of inertial or wave propagation effects. The DYNA3D implementation is compared to the results obtained for a "one-element" EPIC model that is constrained laterally, but subjected to a slowly increasing and then decreasing axial force (Johnson and Holmquist 1993). Figure 2 illustrates the DYNA3D uniaxial strain input history representing loading and unloading of the ceramic in the x-coordinate direction

at constant strain rate. The strain history is analytically described by the sawtooth function

$$\mu(t) = 5tH(t)/100 - (t-1)H(t-1)/10, \tag{13}$$

where $H(t)$ is the Heaviside step function.

3.1 JH-2 Model

The material response is illustrated using a series of figures depicting behavior of a surrogate ceramic material subjected to uniaxial strain history. Model constants are given in Johnson and Holmquist (1993) but are reproduced here in Table 2 (case C) for all plots shown in the following sections. Figures 3, 4, and 5 illustrate the stress response of the ceramic in the respective x, y, and z coordinate directions, where x is the loading direction. Figure 6 shows the continuous pressure vs. time behavior. The plot of effective stress vs. pressure (Figure 1) demonstrates validation of the JH-2 model implementation into DYNA3D by comparison with plots in Johnson and Holmquist (1993) (Figure 4 in that reference). Figure 1 also compares the JH-2 model results superimposed upon the analytical expressions given in equations 3 and 4 for intact $D = 0$, and fully fractured $D = 1$ ceramic, respectively. As previously described in Johnson and Holmquist (1993), the material response for this load history is quite complex and can be described by referring to the letters a–f in Figure 1. From the unstressed state, the material begins to load elastically to point a, which intersects the intact strength curve (equation [3]) in Figure 1. The material begins to "soften" as damage accumulates from point a ($D = 0$) to b ($D = 1$), where the fracture strength curve (equation [4]) is intersected. The material continues to flow plastically from point b to c along the fracture strength curve and reaches a maximum pressure of 7.25 GPa at point c corresponding to the maximum compression of $\mu = 0.05$. The material then unloads elastically from point c to d where the effective stress is zero. From point d to e the unloading continues and the axial deviatoric stress becomes tensile; the fracture stress is encountered at point e and continues to unload along the fracture strength envelope to point f. In the DYNA3D example, the stresses do not return to zero as in the example provided in Johnson and Holmquist (1993) because the former is under strain control and there are residual stresses induced by yielding, whereas the latter is under stress control.

3.2 JH-3 Model

The JH-3 model was also implemented into DYNA3D since recent work indicates that the defeat mechanism known as projectile dwell can be more accurately simulated using the JH-3 model than the JH-2 model when it is used in conjunction with general particle algorithms (GPA) (Beissel and Johnson 2001). The stress response of the JH-3 model for the surrogate ceramic material is shown in Figures 7, 8, and 9 when subjected to the uniaxial strain history in the x coordinate direction (equation [13]). Figure 10 shows the discontinuous pressure vs. time behavior resulting from the abrupt strength loss in the ceramic during failure. Interestingly, the JH-3 model predicts the presence of jump discontinuities in the x, y, and z stresses during failure that can be contrasted to the continuous stress response predicted

by the JH-2 model (e.g., compare Figures 3, 4, and 5 [JH-2 model] with Figures 7, 8, and 9 [JH-3 model]). In particular, the JH-3 model predicts that a jump decrease should occur in the loading direction in a uniaxially strained ceramic with simultaneous jump increases in the lateral stress components. For the JH-3 model, the effective stress continues to increase from point a to b′ as damage accumulates, providing the phenomenological mechanism for dwell; failure in the ceramic occurs instantaneously from point b′ to c′ (Figure 11). The "kink" in the stress drop from point b′ to c′ in Figure 11 is due to the ceramic bulking phenomenon that occurs in a single cycle in the algorithm; if bulking is not permitted to occur during failure, i.e., $\beta = 0$, then the effective stress drops straight downward to the fully fractured strength curve. In contrast, the effective stress for the JH-2 model gradually degrades as damage accumulates, from point a to b in Figure 11.

3.3 Impact Onto Ceramic Targets

The behavior of the Johnson-Holmquist ceramic model is further studied using a one-dimensional (1-D) simulation whereby a 2-in-thick ceramic target is subjected to impact by a semi-infinite, linear elastic flyer plate travelling at an initial velocity of 2×10^4 in/s. The finite-element model geometry is identical to that reported in previous work on impact into functionally graded elastic media where simulation results compared well to closed-form analytical solutions under transient, uniaxial strain, impact loading (Scheidler and Gazonas 2001). The DYNA3D simulations used 60 uniformly spaced hexahedral elements through the thickness of the ceramic target using the ceramic material constants provided in Table 2 (case C). The density and Young's modulus of the flyer plate was 1.8603×10^{-3} $\mathrm{lb}_f \mathrm{s}^2/\mathrm{in}^4$, and 7.583×10^7 psi, respectively. It is seen that the axial and lateral stresses at the center of the JH-2 ceramic target increase monotonically, level-off, and then decrease during the plate impact event (Figure 12). However, for the JH-3 ceramic model, the axial stress increases monotonically, then instantaneously decreases during failure of the ceramic depicted by the arrow at a in Figure 13. The lateral stresses instantaneously increase during failure of the ceramic as depicted by the arrow at b in Figure 13. Since simulations of plate impact tests on ceramics stressed to failure reveal different behaviors for the JH-2 and JH-3 models, plate impact experiments which simultaneously monitor both axial and lateral stresses would aid in verification of the stress predictions provided by these ceramic material models.

4. Summary

This report has described the implementation of a fully 3-D, rate, pressure and damage-dependent constitutive model for brittle materials such as ceramics into the explicit, Lagrangian finite element code DYNA3D. Both the JH-2 and JH-3 ceramic models have been successfully implemented, and their behaviors are compared using the material driver capability present in DYNA3D that permits investigation of fundamental material behavior in the absence of inertial or wave propagation effects. The DYNA3D implementation compares well with results obtained for a "one-element" EPIC model that is constrained laterally, but sub-

jected to a slowly increasing and then decreasing axial force (Johnson and Holmquist 1993).

The JH-3 model was also implemented into DYNA3D since recent work indicates that the defeat mechanism known as projectile dwell can be more accurately simulated using the JH-3 model than the JH-2 model when it is used in conjunction with GPA's. Projectile dwell is phenomenologically modelled using the JH-3 model by essentially delaying the onset of failure, or the decrease in effective stress, until the ceramic is fully damaged, i.e., $D = 1$. Despite this phenomenological advantage over the JH-2 model, the JH-3 model predicts the presence of jump discontinuities in the x, y, and z stresses during failure, which can be contrasted to the continuous stress response predicted by the JH-2 model. In particular, the JH-3 model predicts that a jump decrease should occur in the loading direction in a uniaxially strained ceramic with simultaneous jump increases in the lateral stress components. This behavior is disturbing in view of the uniaxial strain kinematic boundary conditions. Plate impact tests on ceramics stressed to failure with simultaneous monitoring of the axial and lateral stresses (Bourne et al. 1998) would aid in verification of the stress predictions of the JH-2 and JH-3 material model depicted in this report.

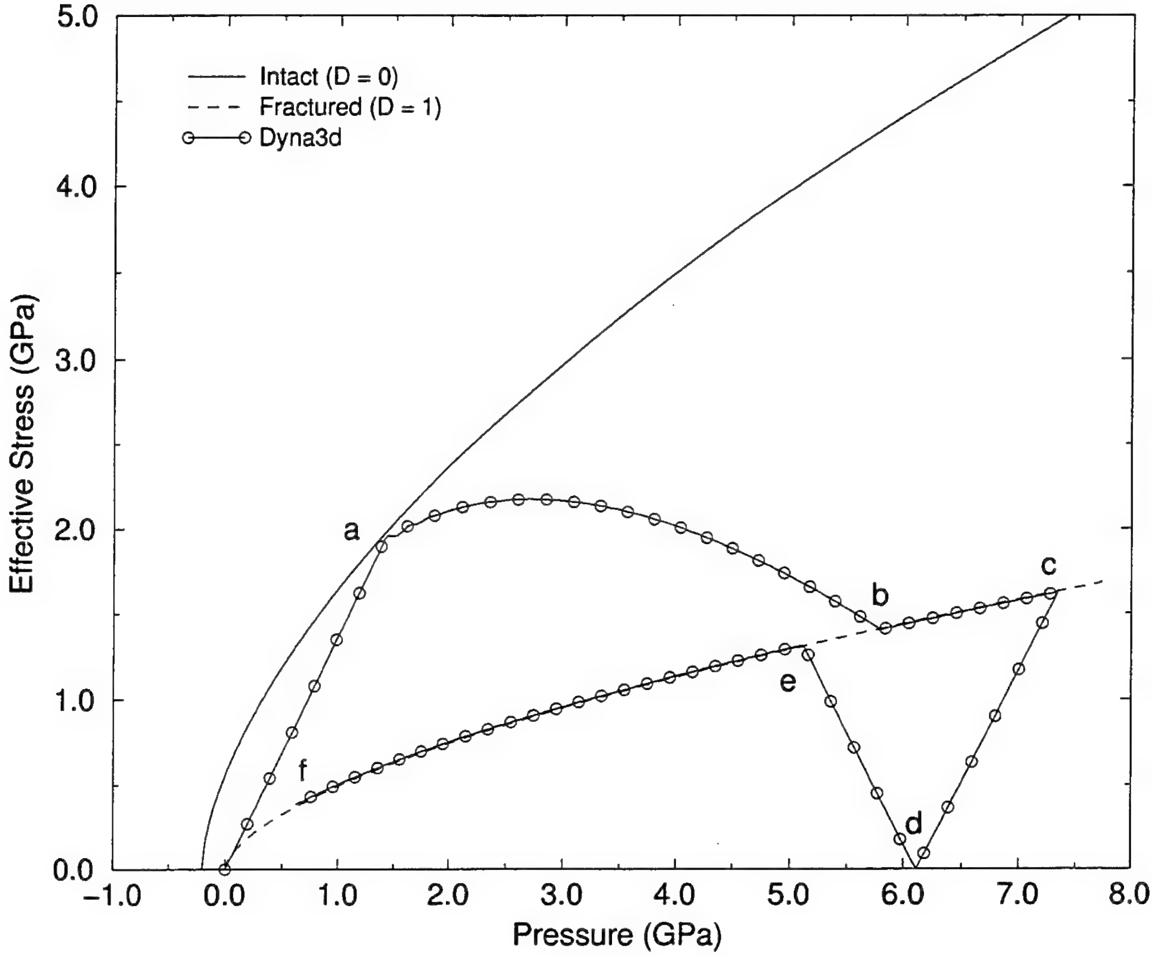

Figure 1. Validation of JH-2 model with analytical expressions, equations (3) and (4).

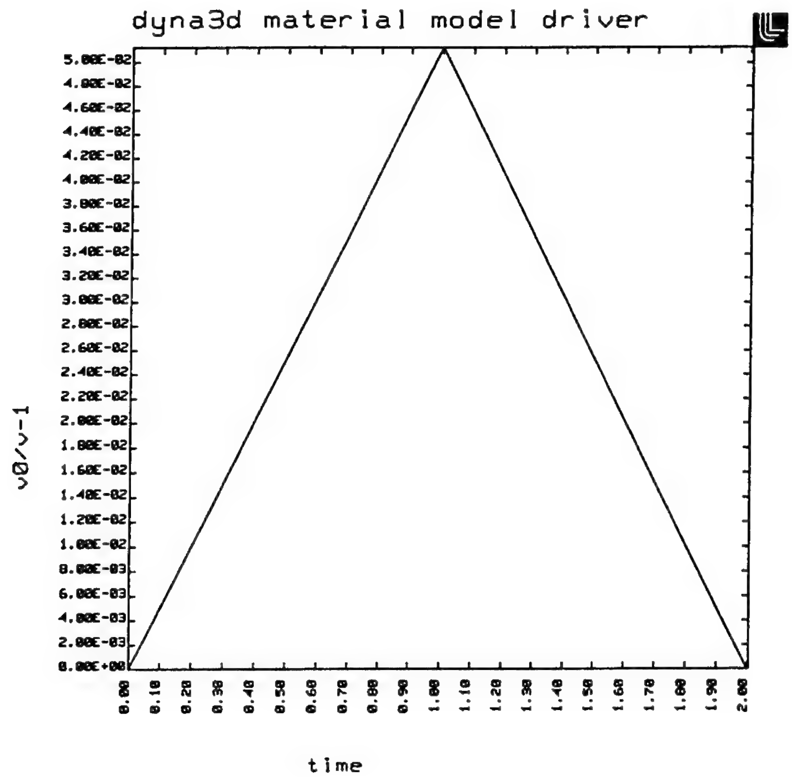

Figure 2. Excess compression $\mu = \frac{V_0}{V} - 1$ vs. time.

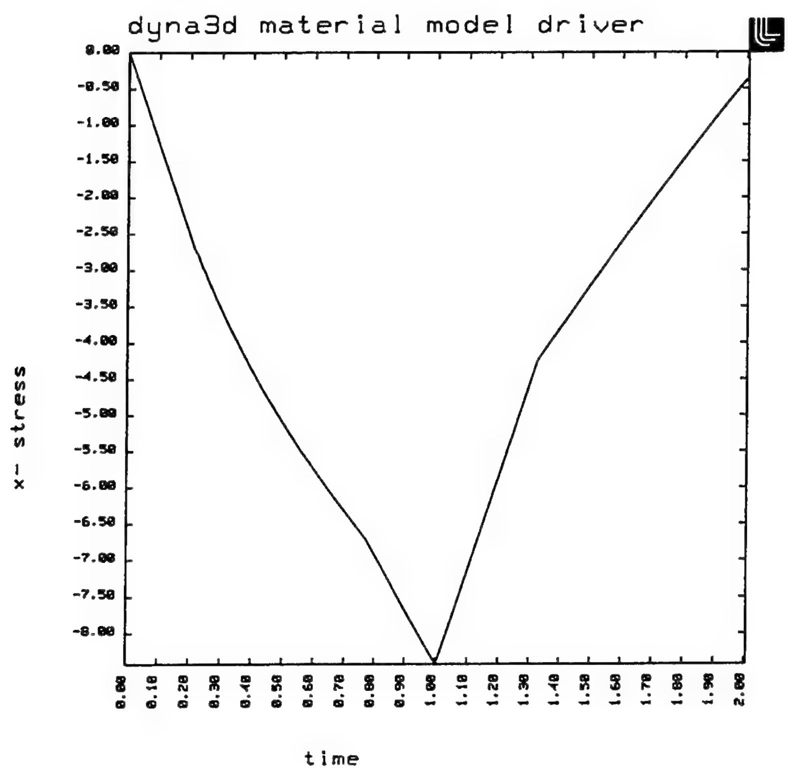

Figure 3. X-stress vs. time (JH-2 model).

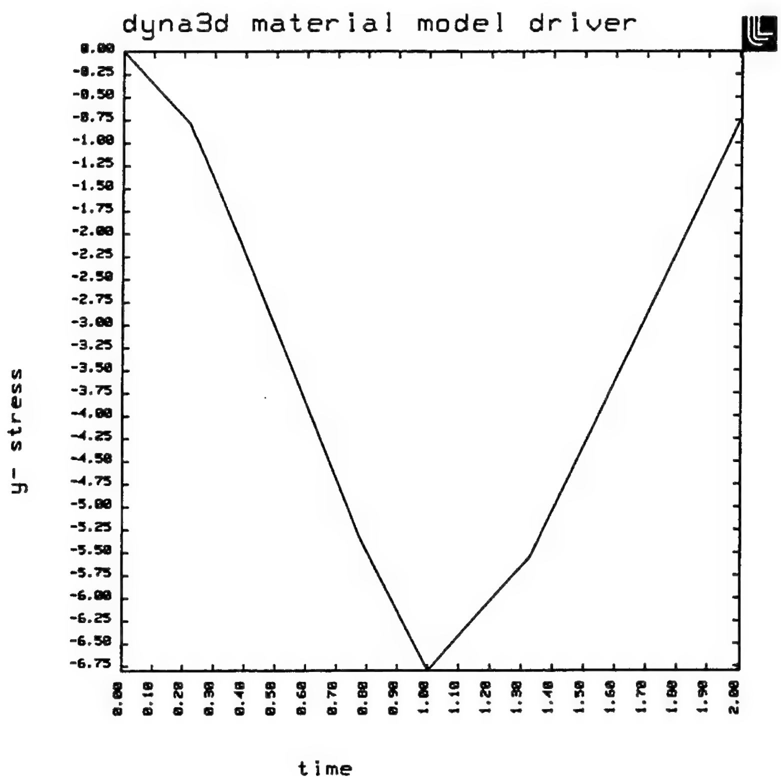

Figure 4. Y-stress vs. time (JH-2 model).

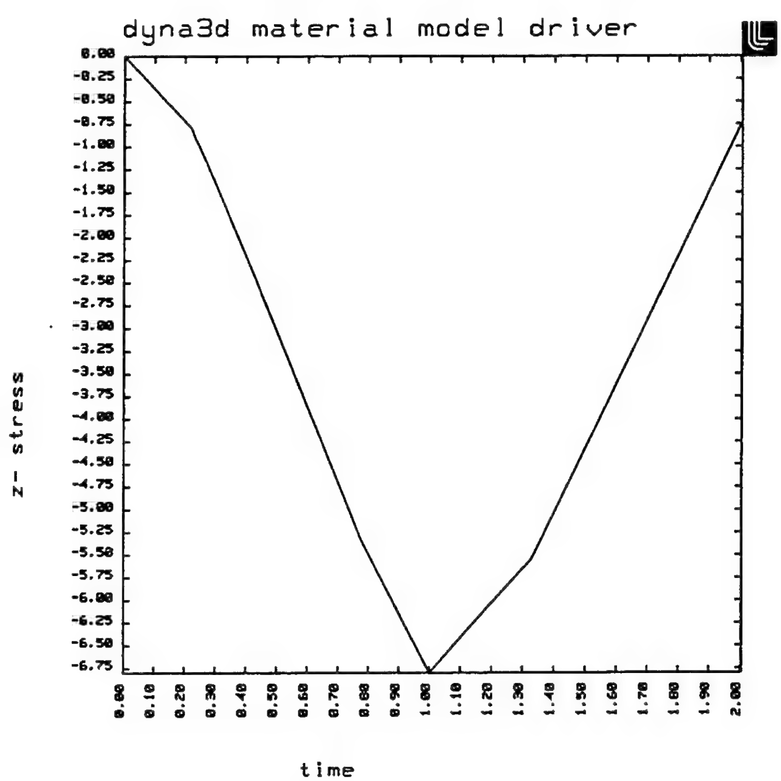

Figure 5. Z-stress vs. time (JH-2 model).

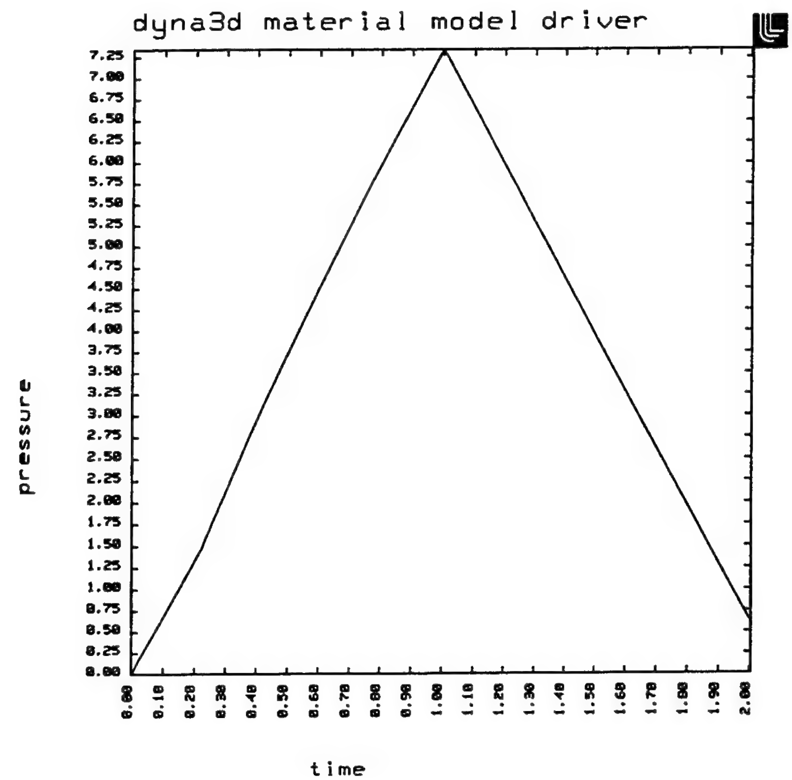

Figure 6. Pressure vs. time (JH-2 model).

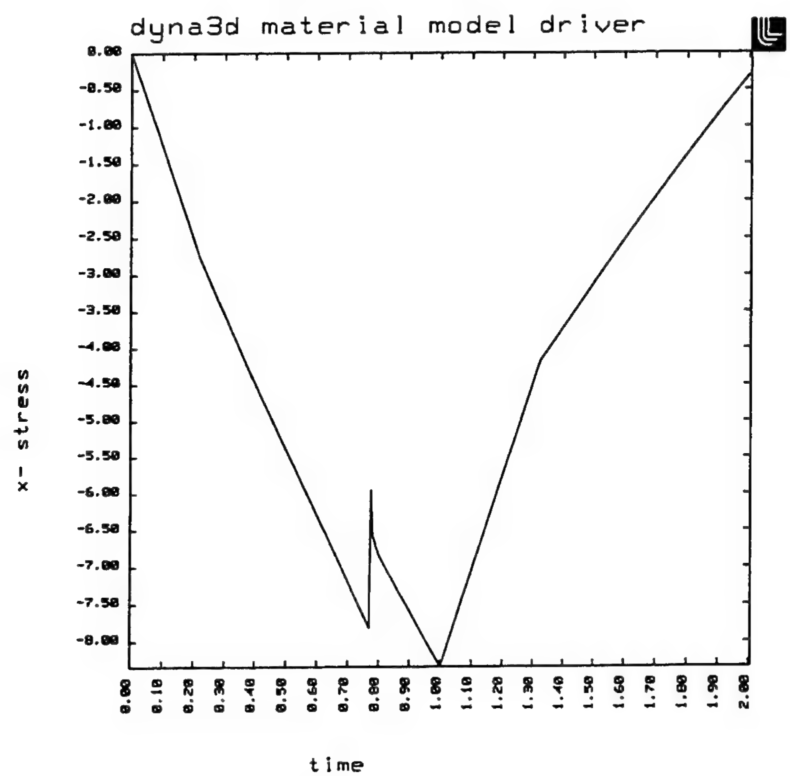

Figure 7. X-stress vs. time (JH-3 model).

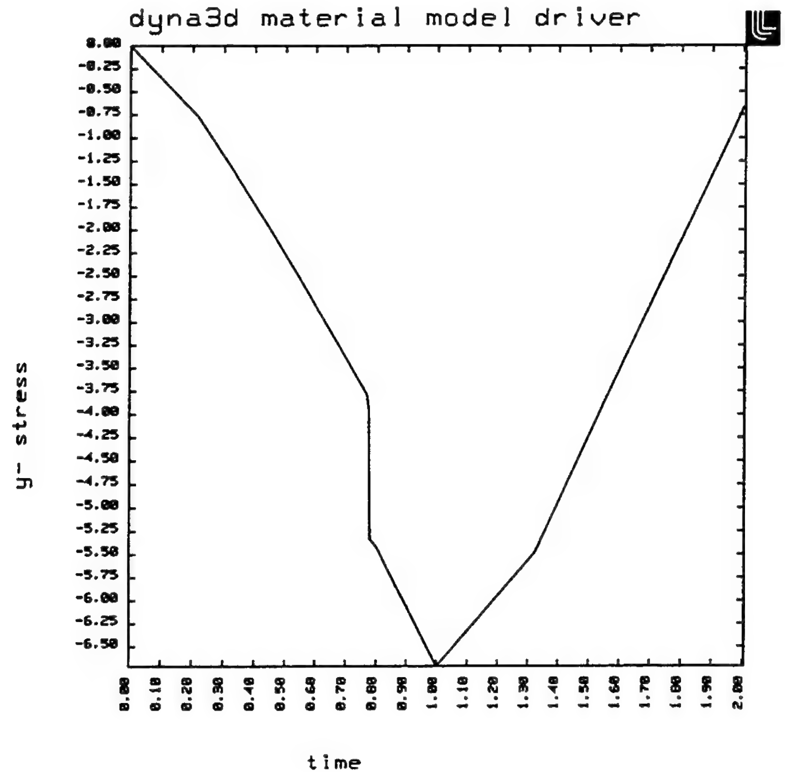

Figure 8. Y-stress vs. time (JH-3 model).

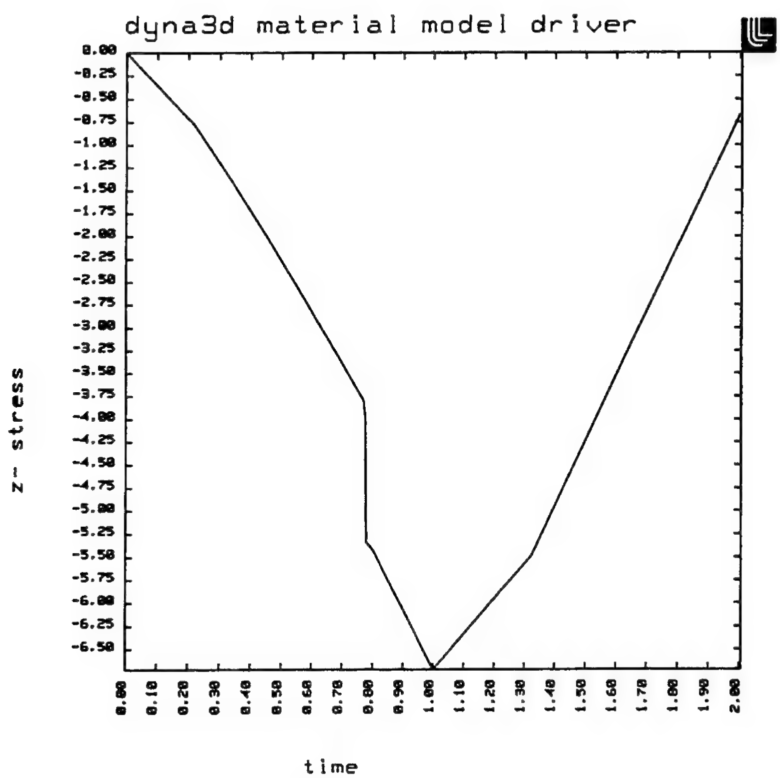

Figure 9. Z-stress vs. time (JH-3 model).

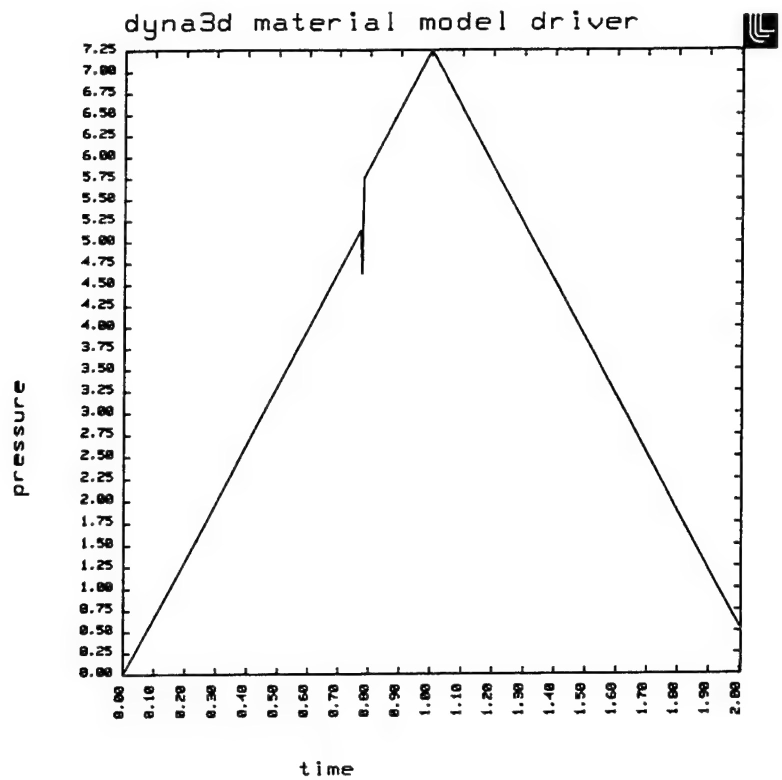

Figure 10. Pressure vs. time (JH-3 model).

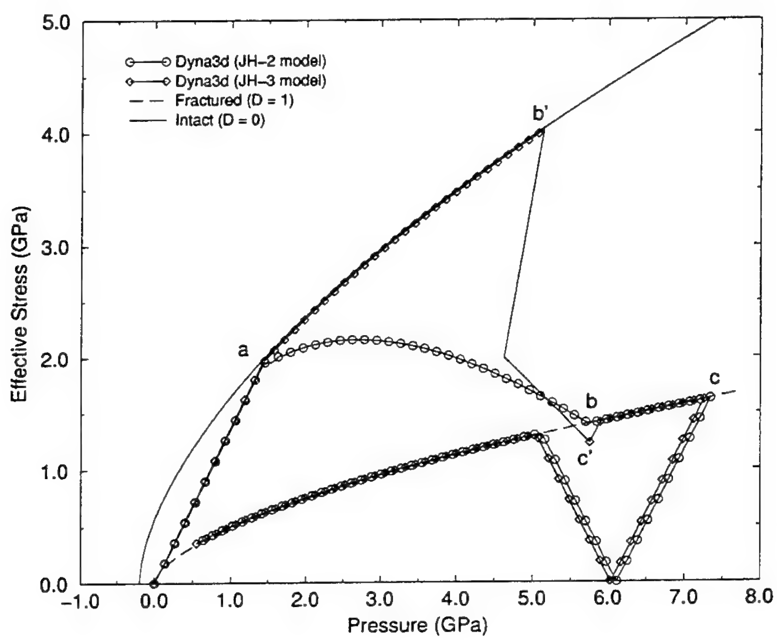

Figure 11. Effective stress vs. pressure for the JH-2 and JH-3 ceramic models.

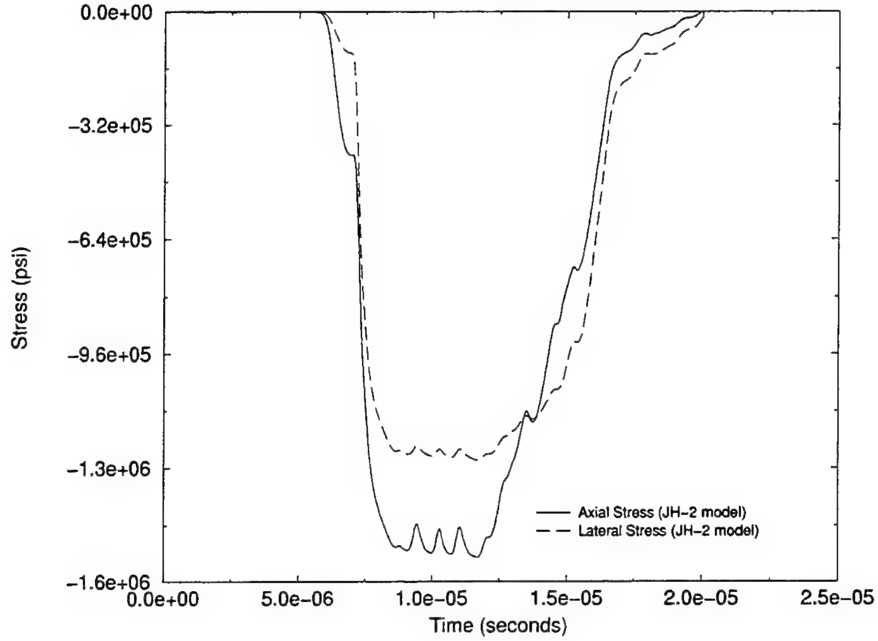

Figure 12. Axial and lateral stress vs. time for 1-D plate impact (JH-2 model).

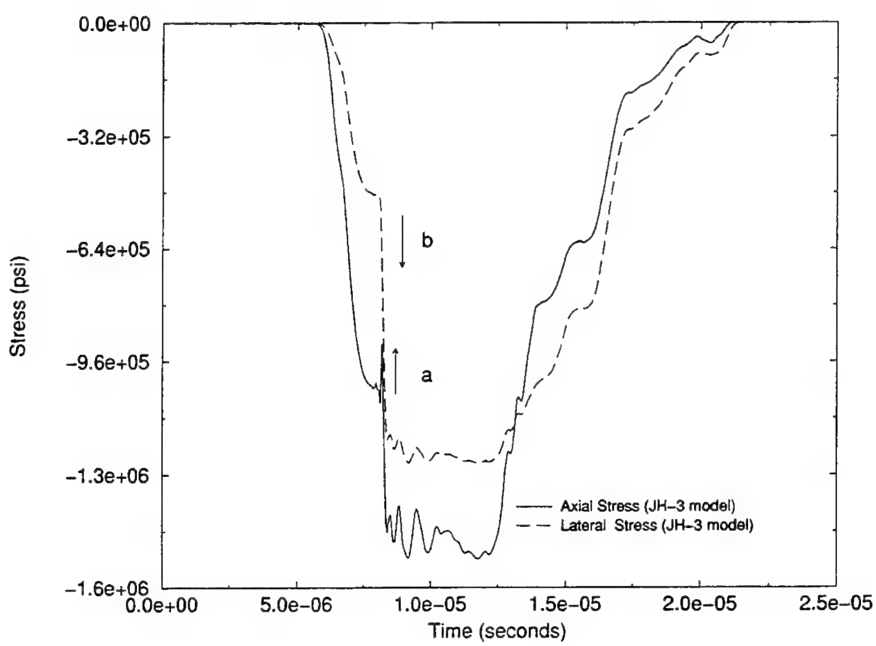

Figure 13. Axial and lateral stress vs. time for 1-D plate impact (JH-3 model).

Table 1. Algorithm for the JH-2 ceramic material model.

1. Calculate trial deviatoric stresses:
$$\sigma_{n+1}^{tr} = \sigma_n + 2\mu\dot{e}\Delta t \ .$$
2. Calculate total effective strain rate $\dot{\varepsilon}$, and $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_o$:
$$\dot{\varepsilon} = \sqrt{\tfrac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \ .$$
3. Calculate the current yield stress σ^* (equation [1]):
$$\sigma^* = \sigma^*(\dot{\varepsilon}^*, D, P^*, T^*) \ .$$
4. Calculate the trial effective stress:
$$\bar{\sigma}^{tr} = \sqrt{\tfrac{3}{2}S^{tr} : S^{tr}} \ .$$
5. Check for yielding:
$\bar{\sigma}^{tr} - \sigma^* > 0$; continue with step 6.
$\bar{\sigma}^{tr} - \sigma^* \leq 0$; go to step 7.
6. Return stresses radially to yield surface:
$$S_{n+1} = \tfrac{\sigma^*}{\bar{\sigma}^{tr}} S^{tr} \ .$$
7. Calculate effective plastic strain rate $\dot{\varepsilon}^p$.
8. Calculate plastic strain to fracture: ε_f^p (equation [7]) .
9. Update damage:
$$D = D + \sum \tfrac{\dot{\varepsilon}^p \Delta t}{\varepsilon_f^p} \ .$$
10. Calculate pressure P and sound speed c.
11. Calculate internal energy loss Δu due to damage (equation [10]).
12. Calculate pressure increment Δp (equation [12]).
13. Update pressure (equation [8]):
$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \ .$$
14. Reduce deviator stresses by energy ratio:
$$S_{n+1} = S_{n+1} \cdot ratio \ .$$
15. Calculate new total stress:
$$\sigma_{n+1} = S_{n+1} + p_{n+1}\delta \ .$$
16. Go to 1.

Table 2. JH-2 model constants for surrogate alumina.

Parameter	Description	Case A	Case B	Case C
ρ_o (g/cc)	Density	3.890	3.890	3.890
G (GPa)	Shear modulus	90.160	90.160	90.160
HEL (GPa)	Hugoniot elastic limit (HEL)	2.790	2.790	2.790
P_{HEL} (GPa)	Pressure component at HEL	1.460	1.460	1.460
σ_{HEL} (GPa)	$\sigma_{HEL} = \frac{3}{2}(HEL - P_{HEL})$	1.995	1.995	1.995
A	Intact strength constant	0.930	0.930	0.930
N	Intact strength constant	0.600	0.600	0.600
C	Strain rate constant	0.000	0.000	0.000
B	Fracture strength constant	0.000	0.000	0.310
M	Fracture strength constant	0.000	0.000	0.600
$S^*_{f\,\max}$	Normalized maximum fracture strength	1.000	1.000	1.000
T^*	Normalized tensile strength	0.137	0.1369	0.137
K_1 (GPa)	Bulk modulus	130.950	130.950	130.950
K_2 (GPa)	EOS constant	0.000	0.000	0.000
K_3 (GPa)	EOS constant	0.000	0.000	0.000
β	Bulking factor	1.000	1.000	1.000
D_1	Damage coefficient	0.000	0.005	0.005
D_2	Damage exponent	1.000	1.000	1.000

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13. ABSTRACT *(Maximum 200 words)*

This report describes the implementation of a fully three-dimensional rate, pressure, and damage-dependent constitutive model for brittle materials such as ceramics into the explicit, Lagrangian finite element code DYNA3D. The model, otherwise known as the Johnson-Holmquist II (JH-2) ceramic model, has also been implemented into CTH, EPIC, and LS-DYNA, and is used extensively in modelling the brittle response of ceramics in armor applications. The DYNA3D material driver was used to verify the model implementation for constant strain-rate input histories (Johnson, G. R., and T. J. Holmquist. "An Improved Computational Constitutive Model for Brittle Materials." *High Pressure Science and Technology*, New York: AIP Press, 1993). Also described is the implementation of the JH-3 ceramic model and capabilities for modelling projectile dwell phenomena. The Johnson-Holmquist series of ceramic models (JH-1, JH-2, and JH-3) is currently being used in a broader program aimed at computational optimization of composite lightweight armor for Future Combat System vehicles.

14. SUBJECT TERMS
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